

Metamirrors

V. S. Asadchy^{1,2}, Y. Ra'di¹ and S. A. Tretyakov¹

¹Department of Radio Science and Engineering, Aalto University
P.O. 13000, FI-00076 Aalto, Finland

²Department of General Physics, Gomel State University, 246019, Belarus
viktar.asadchy@aalto.fi

Abstract – We introduce the concept of non-uniform metamirrors (full-reflection metasurfaces) providing full control of reflected wave fronts independently from the two sides of the mirror. Metamirror is a single planar array of electrically small bianisotropic inclusions. The electric and magnetic responses of the inclusions enable creating controlled gradient of phase discontinuities over the surface. Furthermore, presence of electromagnetic coupling in the inclusions allows independent control of reflection phase from the opposite sides of the mirror. Based on the proposed concept, we design and simulate metamirrors for highly efficient light bending and near-diffraction-limit focusing with a sub-wavelength focal distance.

I. INTRODUCTION

Metasurfaces are electrically thin composite layers with engineered electromagnetic properties. Through the use of metasurfaces, full control over amplitude and phase of reflection and transmission becomes possible. Transparent metasurfaces [1], absorbing sheets [2], full-reflection layers with arbitrary phase of reflection (metamirrors, considered here) [3] are only some examples demonstrating novel and exciting properties unavailable with natural materials. Using in-plane non-uniform metasurfaces it becomes possible to emulate the properties of transmit-arrays [4]-[6]. Another capability provided by non-uniform metasurfaces is near-diffraction-limit focusing [7, 8]. As it was shown in [3] and [8], in order to create a phase variation of the reflection/transmission spanning a 2π range, both tangential electric and magnetic currents on the metasurface are needed. Thus, such metasurfaces must possess a finite thickness to provide necessary magnetic loop currents. Metasurfaces supporting only electric surface currents [4, 6, 7] have very low efficiency (less than 25%). Furthermore, known metasurfaces with only electric surface currents operate only with one specific polarization of incidence. Recent works [5] and [8] have demonstrated highly efficient transmit-arrays of polarizable particles providing both electric and magnetic polarization currents to generate prescribed wave fronts. However, they operate only with one polarization of incidence and allow control only over transmission.

Here, we present a new metasurface concept (so-called metamirror) providing full control of reflected wave fronts. Conventional sub-wavelength reflectarrays [9] consist of closely spaced electrically small patches on a grounded substrate. But the ground plane forbids transmission at all frequencies and limits properties from the opposite side. We utilize the idea of uniform full-reflection sub-wavelength metasurfaces proposed in [3] and develop it for realization of specific non-uniform phase distributions of reflected plane waves. The design represents a single planar array of specifically shaped resonant bianisotropic particles possessing omega electromagnetic coupling. The electromagnetic coupling is crucial in order to create all necessary phase variations of the reflection from the two sides of the metamirror. It allows full tailoring of co-polarized reflection for arbitrary polarized normally incident plane waves. At the same time, due to precise tuning, the structure can approach 100% efficiency. The designed metasurfaces are electrically thin since the inclusions have dipolar response. Moreover, the omega electromagnetic coupling enables engineering asymmetric response from metasurfaces (e.g., negative refraction from one side and sub-wavelength focusing from the opposite side of the surface) [3]. Although here we realize the concept of functional metamirrors only in the microwave frequency range, it can be applied to higher frequencies as well.

II. ANOMALOUS REFLECTION

We design a metasurface to efficiently reflect normally incident plane waves to an arbitrarily chosen angle $\phi = 45^\circ$ from the normal. The metasurface consists of a sub-wavelength periodical planar array of bianisotropic omega inclusions. Since the array period is sub-wavelength, the induced moments can be modelled as surface-averaged electric and magnetic surface currents that radiate secondary plane waves. At the resonance, the metasurface with adjusted inclusion density totally reflects incident waves. Precise tuning the phases of scattered waves from each inclusion allows us to tailor the front of the reflection from the metasurface.

In order to realize anomalous reflection, a linear phase variation along the interface is required. Using the principle of phased arrays, it is simple to show that the reflected wave front is deflected to an angle ϕ if the metasurface provides a linear phase variation spanning 2π range with the periodicity $d = \lambda / \sin \phi$. The use of sub-wavelength inclusions ensures homogeneous (in the sense that the averaged electromagnetic response varies smoothly over the structure) phase variation along the interface. In our design for the microwave frequency range we use copper wire omega particles embedded in a dielectric material with the permittivity $\epsilon_r = 1.03$ and thickness 40 mm along the y -axis (see Fig. 1a). The super-unit-cell (shown as a blue box) consists of 6 particles providing discrete phase

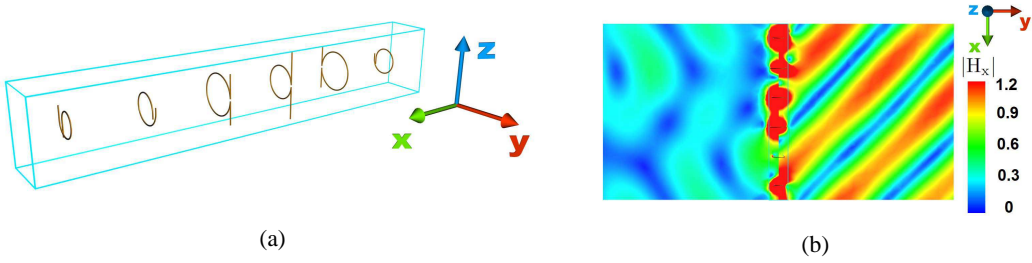


Fig. 1: (a) A unit cell of the metasurface providing a linear phase variation of the reflection spanning a 2π range. The dielectric substrate is not shown for clarity. (b) Magnetic field distribution (normalized to the magnetic field of the incident wave) of the transmitted (on the left side) and reflected (on the right side) waves. The metasurface is illuminated by a normally incident z -polarized plane wave at 1.15 GHz.

shifts that approximate homogeneous electromagnetic response. The operating frequency of 1.15 GHz is chosen. At this frequency the cell period along the x -axis is $d = \lambda / \sin 45^\circ = 369$ mm. The unit cell is repeated also along the z -axis with the periodicity $d/6 = 61.5$ mm. The shape and dimensions of the particles were optimized by numerical simulations in order to create the required discrete phase shifts: $0^\circ, 60^\circ, 120^\circ, 180^\circ, 240^\circ, 300^\circ$. An incident plane wave impinges on the metasurface from the $+y$ -direction with the electric field parallel to the z -axis. Fig. 1b shows magnetic field distribution of the reflected and transmitted waves (Ansoft HFSS simulations). The phase front of the reflection is indeed planar and deflected 45° with respect to the normal. 10.3% of the incident power is transmitted and 4.4% is absorbed by copper wires. Reflectance in this case is 85.3% and can be further increased by inclusions optimization. Despite the thickness of the designed metasurface $\lambda/7.6$ is already quite small, it can be decreased further by choosing different particle shapes.

III. NEAR-DIFFRACTION-LIMIT FOCUSING AT SUB-WAVELENGTH DISTANCES

Another example demonstrating the flexibility and uniqueness of non-uniform metamirrors is focusing metasurfaces showing extremely strong wave-gathering ability. The metamirror concept allows us to design a conceptually new kind of a lens: one consisting of an ultimately thin single layer of resonant dipolar inclusions providing near-diffraction-limit focusing of electromagnetic energy at any focal distance and at any point. Moreover, asymmetric response from different sides of the lens can be achieved providing the extreme freedom for engineering. Since the metalens is planar, it does not possess spherical aberrations. The proposed concept can be applied for any frequency range.

Realization of lens response requires certain phase variations along the surface ensuring that the scattered fields from all inclusions constructively interfere in the desired point. To demonstrate the lensing effect, we designed a single-layer metamirror composed of 6 concentric arrays of bianisotropic omega inclusions (see Fig. 2a). The concentric arrays provide the desired phase shifts from the center to the edges: $-80^\circ, -54^\circ, -2^\circ, 65^\circ, 140^\circ, -140^\circ$.

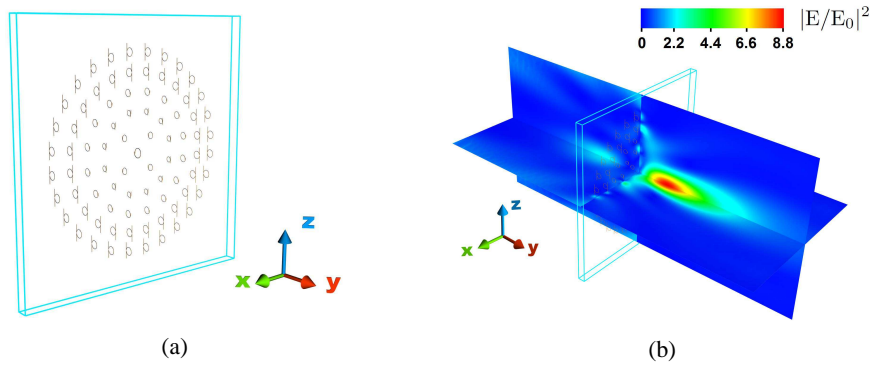


Fig. 2: (a) A single-layer metalens. The blue box denotes the dielectric substrate. (b) Power density distribution (normalized to the incident power density) of the reflection (the $+y$ half-space) and transmission (the $-y$ half-space). Power intensity maps are depicted on two orthogonal cross-section planes (the xy and yz -planes).

The working frequency and the supporting dielectric slab (marked as a blue box on the figure) are the same as in the previous example. The dimensions of the metalens: the radius is 1.4λ and the thickness is $\lambda/7.6$. In order to demonstrate the power of the concept, the inclusions are designed to confine electromagnetic energy in a spot at an extremely small focal distance 0.6λ . An incident plane wave impinges on the metalens from the $+y$ -direction (the electric field parallel to the z -axis). Fig. 2b shows the simulated power distribution of the reflection and transmission from the metalens at 1.155 GHz. Very weak transmission in the far-zone is caused by diffraction effects on the edges of the metasurface. The metalens effectively reflects the wave and focuses it tightly near the diffraction limit to a spot of only $2.8\lambda \times 0.9\lambda$ size ($1/e^2$ beamwidth). The extremely strong focusing ability of the designed metalens provides the focal length of only 0.73λ and high energy gain of 8.8 in the spot. The f-number (the ratio of the lens's focal length to its diameter) for the designed metalens comes to 0.26 and can be further decreased by increasing the lens' diameter. Such small f-number of the metalens allows of gathering more power and generally providing a brighter image. These parameters of the designed lens significantly exceed those of other metamaterials-based lenses, e.g. [7, 8].

IV. CONCLUSION

Our results show that the metamirror concept enables extreme independent control over reflection from the two sides of the surface and allows of designing ultimately thin, 100%-efficient, polarization-insensitive devices with desired properties. Similar full control over transmission can be accomplished through the use of the Babinet-inverted design.

REFERENCES

- [1] Y. Ra'di, V. S. Asadchy, and S. A. Tretyakov, "One-way transparent sheets," *Physical Review B*, vol. 89, p. 075109, 2014.
- [2] Y. Ra'di, V. S. Asadchy, and S. A. Tretyakov, "Total absorption of electromagnetic waves in ultimately thin layers," *IEEE Trans. Antennas Propag.*, vol. 61, no. 9, pp. 4606–4614, 2013.
- [3] Y. Ra'di, V. S. Asadchy, and S. A. Tretyakov, "Tailoring reflections from thin composite metamirrors," *arXiv: 1401.1677*.
- [4] N. Yu, P. Genevet, M. A. Kats, F. Aieta, J. P. Tetienne, F. Capasso, and Z. Gaburro, "Light propagation with phase discontinuities: generalized laws of reflection and refraction," *Science*, vol. 334, no. 6054, pp. 333–337, 2011.
- [5] C. Pfeiffer and A. Grbic, "Metamaterial Huygens' surfaces: Tailoring wave fronts with reflectionless sheets," *Phys. Rev. Lett.*, vol. 110, p. 197401, 2013.
- [6] N. K. Grady, J. E. Heyes, D. R. Chowdhury, Y. Zeng, M. T. Reiten, A. K. Azad, A. J. Taylor, D. A. Dalvit, and H. T. Chen, "Terahertz metamaterials for linear polarization conversion and anomalous refraction," *Science*, vol. 340, no. 6138, pp. 1304–1307, 2013.
- [7] X. Ni, S. Ishii, A. V. Kildishev, and V. M. Shalae, "Ultra-thin, planar, Babinet-inverted plasmonic metalenses," *Light: Science & Applications*, vol. 2, e72, 2013.
- [8] F. Monticone, N. M. Estakhri, and A. Alù, "Full control of nanoscale optical transmission with a composite metascreen," *Phys. Rev. Lett.*, vol. 110, p. 203903, 2013.
- [9] D. M. Pozar, "Wideband reflectarrays using artificial impedance surfaces," *Electronics Letters*, vol. 43, no. 3, pp. 148–149, 2007.